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Assessment of Stator Winding Insulation

Part 2 – Tests on Inservice Machines

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This paper presents the test results and analysis made on several machines at site. Case studies are employed to illustrate the usefulness of measurements on the stator windings in service.

1.0 INTRODUCTION

The progressive deterioration of high voltage machine insulation is assessed through non destructive techniques like measurement of Insulation Resistance, Polarization Index, Dissipation factor, Loss angle and Capacitance, Partial Discharge (PD) measurements, mainly for trend analysis. Though a single test cannot indicate the condition of the stator winding insulation a reasonable assessment can be made by combining analysis made by several test results. Based on these techniques several motors and generators were tested at some of the industries, hydro, thermal and nuclear power stations. This paper presents the test results and analysis made on several machines at site. Case studies are employed to illustrate the usefulness of measurements on the stator windings in service.

2.0 CASE STUDIES

Case (1) 6.6 kV, 5.1 MW Synchronous Motors (Class B)

The Diagnostic tests were carried out on two identical 12 year old 6.6 kV 5.1MW Synchronous motors installed in a petro chemical plant. The results obtained on the machines are summarized in Table 1. As it can

TABLE 1

Motor	Phase	Tan Delta	Tan Delta Tip-up	Capacitance Tip-up(%)	I.D.E. µJ/pF/Cycle	Vi (kV)
A	R	0.0694	0.03515	10.3	1.79	2.10
	Y	0.0697	0.0326	8.5	1.98	2.10
	B	0.0709	0.0385	11.7	1.96	2.15
B	R	0.0848	0.0296	8.5	1.52	2.11
	Y	0.0826	0.0305	8.6	1.7	2.13
	B	0.0861	0.0299	7.5	1.65	2.10

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be seen from the Table, Tan delta tip-up, Capacitance tip up and IDE values were high for class B insulation. These results indicate the severe deteriorated condition of the stator insulation of both the machines. During IDE measurements on R-phase of Motor A, the loop trace obtained on the screen of Dielectric loss Analyzer was unstable at about 3.7 kV onwards.

It was suspected that the instability of pattern may be due to the presence of severe slot or end winding discharges in the winding. These discharges are detrimental to the insulation as they develop quickly and ultimately lead to the failure. Further the discharge inception voltage was low for both the machines. After analysing the results in detail the Company was advised to enhance the remaining useful service lives of the machines by replacing the line end coils by neutral coils and vice versa of the both the stators. Rewinding of the stator was carried out and varnish applied after interchanging line and neutral end coils. The Diagnostic tests were repeated on the completed stators Table 2 gives the test data obtained on the machines after the Refurbishment.

TABLE 2

Motor	**Phase**	**Tan Delta**	**Tan Delta Tip-up**	**Capacitance Tip-up(%)**	**I.D.E. μJ/pF/Cycle**	**Vi (kV)**
A	R	0.0405	0.0315	7.1	2.9	2.10
	Y	0.0430	0.02895	6.95	2.5	2.15
	B	0.044	0.0335	8.57	2.9	2.10
B	R	0.0540	0.0266	7.09	2.2	2.15
	Y	0.0550	0.02975	8.30	2.1	2.15
	B	0.0545	0.03375	11.6	2.4	2.10

These results indicated no improvement in the state and quality of the insulation. The DLA pattern obtained on R-phase of Motor A was again unstable. The user was cautioned about the precarious condition of the stator insulation of the machine. This fact was confirmed when the stator of motor A failed just one month after the refurbishment was given.

Case (2) 11 kV, 7000 H.P. Synchronous Motors (class B)

These two identical, 18 years old class B motors are operating in the Ammonia plant of a Fertilizer Company. The machines are located close to each other in the plant and operating conditions are same. The Diagnostic tests were conducted on the machines in order to assess the insulation condition of the stators. The results of the test obtained are presented in the Table 3.

TABLE 3

Test Parameter	**Motor 1**	**Motor 2**
Tan delta	0.0686	0.036
Tan delta tip-up	0.00615	0.00148
Capacitance tip-up(%)	0.3535	0.3325
I.D.E. μJ/pF/Cycle	0.64	0.32
Discharge inception Voltage (kV)	4.0	5.0

The results of the tests indicated significant variations in the general conditions of the machines. The motor No.1 showed comparatively higher values than the other motor even though the stress levels and other operating conditions were same. Normally identical machines situated at a particular location exhibits comparable results. In this case the results obtained were contradictory. Tan delta, tan delta tip-up, IDE and V_i clearly indicated that the stator insulation of the Motor No. 1 was not in good condition. During the technical discussion with the Engineers of the Company it was revealed that the cooling system of the motor No. 1 had failed just few months prior to the date of tests and stator winding got over heated. It seems the shut down of the machine was taken only when the smoke emanating from the enclosure of the machine was noticed. After this accident, the user company wanted to know the condition of the machine No. 1.

The results of the tests were analyzed in detail in order to assess the quality of the stator insulation. Here the interesting fact was that the capacitance tip-up values of the machines were comparable. The experience obtained in the laboratory on the investigation of ageing phenomena of HV machine insulation has proved that the deterioration of the insulation, which is an irreversible process, is invariably associated with a large capacitance tip-up along with other parameters. As both the machines exhibited comparable values of capacitance tip-up, it was concluded that the insulation condition of stator of motor No. 1 was also satisfactory, even though its present state was not comparable with that of the other. It was recommended to carry out the tests after two years in order to monitor the condition of the stator insulation. The results of the subsequent measurements on both the machines two years later confirmed our prediction. The results are presented in Table 4.

TABLE 4

Test Parameter	Motor 1	Motor 2
Tan delta	0.0395	0.0396
Tan delta tip-up	0.00253	0.00265
Capacitance tip-up(%)	0.37	0.38
I.D.E. µJ/pF/Cycle	0.85	0.825
Discharge inception Voltage (kV)	4.4	4.4

The class B insulation system being thermoplastic in nature could regain its insulating properties at the operating temperature in the course of its service. Both the machines are operating satisfactorily and thus diagnostic tests gave the user confidence about the reliability of the machines.

Case (3) 3.3 kV, 210 kW Induction Motor (class B)

The results of the Diagnostic tests obtained on two 18 years old, 3.3 kV, 210 kW Induction Motors installed in a Fertilizers Company are tabulated in Table 5. Tan delta tip-up and capacitance tip-up values were quite high for such insulation even though they have not reached the alarming level. Based on these results it was concluded that the condition of the stator insulation of both the machines was not satisfactory. It was recommended for refurbishment of the stators in order to increase the remaining useful service lives of the machines. The User Company accepted the recommendations and initiated action to give a refurbishment of the stators.

TABLE 5

Motor	Tan Delta	Tan Delta Tip-up	Capacitance Tip-up(%)	I.D.E. µJ/pF/Cycle	Vi kV
C	0.0084	0.0163	2.103	0.54	1.80
D	0.0058	0.01725	3.44	0.473	1.82

TABLE 6

Motor	Tan Delta	Tan Delta Tip-up	Capacitance Tip-up(%)	I.D.E. µJ/pF/Cycle	Vi kV
C	0.0353	0.00175	0.67	No discharges	More than 2kV
D	0.0287	0.00225	0.44	No discharges	More than 2kV

The physical inspection of the stators reveals that the wedges were loose and damaged and had become black due to accumulation of carbon particles. The stators were given a refurbishment with the new magnetic wedges and varnish. The Diagnostic tests were again carried out on the stators after refurbishment in order to check the state and quality of the insulation. The results are furnished in Table 6.

These results revealed that the insulation condition of the stators has improved considerably after rewedging and varnishing of the stators.

Case (4) 11 kV, 17 MW and 21.25 MW Generators

(a) Plant history

Six generators were commissioned during 1955 and 1959 in two stages. These Generators are of Class B insulation and are in service for more than 50 years operating at high load factor. Station Records indicate the average annual generation of power station is 675 MU as against 525 MU and has been delivering 114.5 MW on CMR basis. As reported by the station authorities and as per the records available in the power station, there has been frequent failure of generator stator coils and some of the coils have been replaced and the machines are put in operation. The electro mechanical voltage regulators of all the six generators are increasingly giving trouble and it is reported that due to non availability of spares, maintenance has become difficult task. Many a number of times the eroded runner vanes have been repaired. The wicket gates of Unit 3 had failed due to heavy pitting/erosion. The spherical valves and centrally balanced valves of the pen stocks are not functioning satisfactorily. They are not closing completely. The pressure regulators provided are not functioning properly. The instrumentation and control and the governing system have become unreliable. The wear plates, wear rings, shaft seals are worn out/eroded badly resulting in heavy leakage of water. Further the other major troubles experienced are; the C.B valves/the spherical valves near the power house in the high pressure penstocks are not functioning properly. Most of the wicket gates of the units have eroded.

(b) Condition monitoring tests

Condition assessment tests were conducted the on generator insulation in order to assess the insulation deterioration during the years 1994, 1996 and 2008.

Based on the test results of 1994 and 1996, it was opined that the stator insulation has aged quite considerably. As an initial corrective measure, it was recommended to carry out thorough visual inspection and examination of the entire stator winding which will help in detecting visible symptoms of deterioration such as mechanical damage to coil surface and end windings, looseness of coils and wedges, deterioration due to thermal effects and the like.

Accordingly, station authorities initiated action for conducting the visual inspection of the Generators. The visual inspection and examination revealed that the generators are very soiled, particularly in the core portion of the stator bore. The slot wedges have become loose and the wedge material dusty due to rubbing of the wedges against the core iron and leakage of oil has formed a sticky black paste. Further, rust was found on the back side of the core, in the air ducts and on individual segments. Based on the findings it was recommended to thoroughly clean and rewedge.

(c) Analysis: 11 kV, 17 MW Generators

The results of the tests repeated during the year 2008 are presented Tables 7 to 11. Tables 7 and 8 present the data obtained on generator units 1 and 2 respectively. From these Tables it is evident that the first stage Generators, Unit Nos. 1 and 2 show moderate ageing of the insulation.

TABLE 7

RESULTS OF THE IR, TAN DELTA AND PARTIAL DISCHARGE TESTS OBTAINED ON EACH PHASE OF 17 MW GENERATOR UNIT #1 STATOR WINDING

Test Connection	Year	IR (in MΩ) (60 sec)	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD Inception Voltage (kV)	PD Extinction Voltage (kV)	PD Magnitude at Phase Voltage (pC)
R phase	1994	190	2.95	0.2	0.39	0.21	—	—	—
	2008	387	3.59	3.083	0.130	0.22	—	—	No Partial discharge
Y phase	1994	170	2.44	3.39	0.27	0.49	—	—	—
	2008	388	3.80	3.721	0.125	0.20	—	—	No Partial discharge
B phase	1994	190	3.26	3.46	0.31	0.63	—	—	—
	2008	432	3.34	3.758	0.128	0.19	—	—	No Partial discharge

TABLE 8

RESULTS OF THE IR, TAN DELTA AND PARTIAL DISCHARGE TESTS OBTAINED ON EACH PHASE OF 17 MW GENERATOR UNIT #2 STATOR WINDING

Test Connection	Year	IR (in MΩ) (60 sec)	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD Inception Voltage (kV)	PD Extinction Voltage (kV)	PD Magnitude at Phase Voltage (pC)
R phase	1994	310	2.55	3.34	0.41	0.49	—	—	—
	2008	323	2.98	4.377	0.112	0.19	2.2	2.0	8000
Y phase	1994	275	2.10	3.20	0.41	0.42	—	—	—
	2008	340	3.29	4.343	0.143	0.22	2.6	2.2	6000
B phase	1994	275	2.18	3.08	0.46	0.63	—	—	—
	2008	228	4.61	4.362	0.156	0.23	2.3	2.2	6400

TABLE 9

RESULTS OF THE IR, TAN DELTA AND PARTIAL DISCHARGE TESTS OBTAINED ON EACH PHASE OF 21.25 MW GENERATOR UNIT #4 STATOR WINDING

Test Connection	Year	IR (in MΩ) (60 sec)	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD Inception Voltage (kV)	PD Extinction Voltage (kV)	PD Magnitude at Phase Voltage (pC)
R phase	1994	210	2.62	7.57	1.84	5.02	—	—	—
	2008	258	—	10.84	2.352	6.31	—	—	50000
Y phase	1994	230	2.57	8.04	1.59	5.21	—	—	—
	2008	85.6	1.87	10.78	2.406	6.50	—	—	30000
B phase	1994	200	2.90	7.10	2.11	5.25	—	—	—
	2008	75.1	2.16	10.42	2.536	6.75	—	—	24000

TABLE 10

RESULTS OF THE IR, TAN DELTA AND PARTIAL DISCHARGE TESTS OBTAINED ON EACH PHASE OF 21.25 MW GENERATOR UNIT #5 STATOR WINDING

Test Connection	Year	IR (in MΩ) (60 sec)	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD Inception Voltage (kV)	PD Extinction Voltage (kV)	PD Magnitude at Phase Voltage (pC)
R phase	1994	275	3.11	8.18	1.84	5.53	—	—	—
	2008	117	2.31	10.1	2.26	6.27	3.593	3.357	20000
Y phase	1994	265	3.13	7.56	2.01	5.81	—	—	—
	2008	129	2.40	9.26	2.30	6.46	4.991	4.200	30000
B phase	1994	260	3.17	7.57	1.96	5.31	—	—	—
	2008	125	2.35	9.44	2.31	6.45	4.282	3.657	50000

TABLE 11

RESULTS OF THE IR, TAN DELTA AND PARTIAL DISCHARGE TESTS OBTAINED ON EACH PHASE OF 21.25 MW GENERATOR UNIT #6 STATOR WINDING

Test Connection	Year	IR (in MΩ) (60 sec)	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD Inception Voltage (kV)	PD Extinction Voltage (kV)	PD Magnitude at Phase Voltage (pC)
R phase	1994	85	2.53	8.16	1.4	3.81	—	—	—
	2008	147	3.96	8.556	1.90	5.31	2.5	2.0	80000
Y phase	1994	110	2.27	8.19	1.46	4.08	—	—	—
	2008	311	5.09	8.436	1.97	5.58	2.4	1.9	70000
B phase	1994	90	2.33	8.20	1.55	4.40	—	—	—
	2008	393	3.12	8.049	2.20	6.09	2.4	2.0	80000

The IR and PI values of units 1 and 2 lie in the acceptable range for a 51 years old machine indicating that the stator winding is clean and dry. The DC leakage current characteristics obtained on the stator winding showed the magnitude of the leakage current was small and its variation with the test voltage does not exhibit steep slope as shown in the Figs. 1 and 2. These results further confirm that surface conditions of the stator winding are dry.

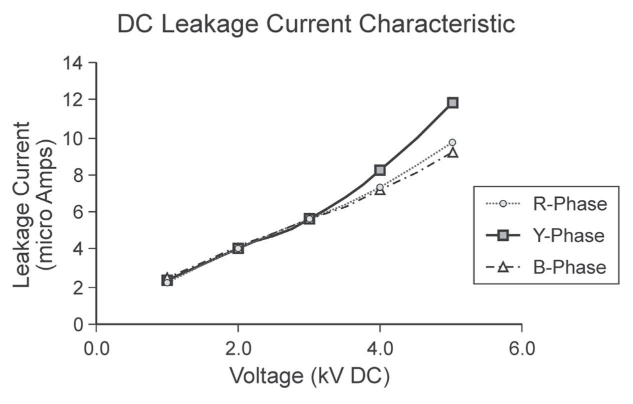

FIG. 1 DC LEAKAGE CURRENT CHARACTERISTIC ON UNIT NO.

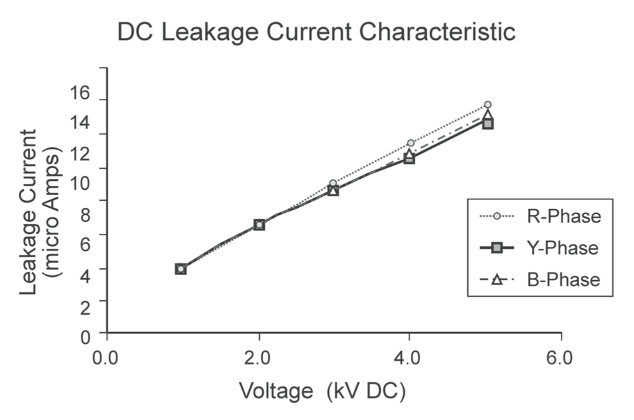

FIG. 2 DC LEAKAGE CURRENT CHARACTERISTIC ON UNIT NO.2

The tan delta values which are the figure of merit of the insulation lie in the normal permissible range for an in-service aged machine. The observed results indicate normal dielectric losses in the stator winding insulation system. The Tan delta tip-up (ΔT) and Capacitance tip-up (ΔC) which indicate the void content are low in the stator insulation system. The surge comparison test showed normal patterns without any distortion indicating no inter turn fault in the stator winding insulation. The winding resistance values all the three phases lie in the normal permissible range.

Based on the above findings it was recommended that insulation condition is quite healthy and to repeat the tests after two years to monitor the trend in ageing as it is an ongoing process.

(d) Analysis : 11 kV, 21.25 MW Generators

Further the data obtained on Generator units No. 4 to 6 are shown in Tables 9 to 11 respectively. From these Tables it is evident that Generator Units 4 – 6 of II stage have high initial values of tan delta and starting of corona discharges at 30% of rated voltage. i.e. about half the phase voltage. Tan delta values obtained on these machines are abnormally high for an in service class B machine. As compared to the base tan delta values obtained in the year 1994, the tan delta increments are too high indicating substantial ageing / deterioration of the stator winding insulation system. The Tan delta tip-up (ΔT) and Capacitance tip-up (ΔC) values are very high for an in service class B machine and indicate substantial ageing of the stator insulation. These high ΔT and ΔC represent higher void content in the insulation. As the machine is 51 years old, the void content have considerably increased with ageing, contributing to increase in ΔT and ΔC.

The partial discharge magnitude at operating phase voltage is abnormally high for an in-service machine. These results indicate highly deteriorated condition of the stator winding insulation. PD inception and extinction voltages are lower than 50% of the operating phase voltage indicating slot end discharges in addition to PD. This is a clear indication that the winding insulation has reached a stage of deterioration where a sudden breakdown can occur and the operational reliability and the availability are very much endangered.

Recommendation

As it is evident in the above Tables 9 to 11, majority of the Generators exhibit substantial ageing / deterioration of their insulation system and have come to the end of their life. As the equipments are already 51 – 53 years old and in view of persistent problems associated with both electrical and mechanical equipment as recorded in the O and M history illustrated above, it was recommended to consider the power station for renovation and modernization with latest technology, refurbishment and retrofitting. With modern class F insulation system, the Generator output power rating can be enhanced to the extent of 20%. The R & M program not only improves reliability and availability of the equipment but also enhances the station power output.

Case (5) 11 kV, 5 MW Hydro Generator

These two generators have been commissioned during 1956 and operating satisfactorily in a dam power house. The non-destructive tests were carried out for the first time during 1991. The user company was contemplating to update the rating of the power station by replacing the existing class-B insulation with class-F system. However with a view to ascertain in the present condition of the machines the company decided to carryout the non-destructive tests on the stators. The results of the tests are tabulated in Table 12.

TABLE 12					
MACHINE NO. 1					
Phase	**Tan Delta @ 0.2 V_L (%)**	**ΔT (%)**	**ΔC (%)**	**IDE µJ/pF/Cycle**	**Maximum Vi**
R	6.97	0.02	1.07	0.42	6.0
Y	6.92	0.02	0.25	0.35	6.0
B	7.09	0.03	0.25	0.28	6.0
MACHINE NO. 2					
Phase	**Tan Delta @ 0.2 V_L (%)**	**ΔT (%)**	**ΔC (%)**	**IDE µJ/pF/Cycle**	**Maximum Vi**
R	6.55	0.07	0.15	0.35	6.0
Y	6.50	0.075	0.46	0.42	6.0
B	6.53	0.095	0.44	0.42	6.0

The results indicated low level of deterioration. It was concluded that the insulation condition of stators of both the machines is healthy. Even now the machines are operating satisfactorily and thus the diagnostic tests gave the user company confidence in the reliable operation of the machines.

Case (6) 11 kV, 37.5 MW Hydro Generator

This class B machine commissioned during 1957 has been working satisfactorily in a dam power house. The non-destructive tests were carried out for the first time with a view to assess the state and condition of the insulation. The results of the tests are tabulated in Table 13.

From the Table it can be seen that the base value of tan delta is high for such an insulation system. This may be attributed to the substantial amount of contamination of the insulation. The low value of Vi and high values of IDE indicate high void content in the insulation. These results indicate considerable amount of deterioration of the insulation. However, with a view to assess the rate of deterioration, it was recommended to carryout diagnostic tests after a year.

Case (7) 11 kV, 144 MVA Hydro Generators

With a view to evaluate the condition of these two class F generators commissioned during 1976 and 1985 detailed visual examination/ inspection and testing of the stator and rotor windings were carried out. The results of this evaluation programme are summarized in Table 14.

TABLE 13					
Phase	**Tan Delta @ 0.2 V_L (%)**	**ΔT (%)**	**ΔC (%)**	**IDE µJ/pF/Cycle**	**Maximum Vi**
R	12.82	0.93	2.54	11.24	3.0
Y	12.20	1.09	2.86	8.72	3.0
B	12.84	1.08	2.70	10.19	3.0

TABLE 14

Test Parameter	Generator No. 1 (1976) R Phase	Generator No. 2 (1985) R Phase
Tan delta (%)	0.95	0.87
ΔT (%)	0.094	0.29
ΔC (%)	0.36	0.36
IDE μJ/pF/cycle	1.37	1.01
Vi (kV)	4.5	5.3
Max. Magnitude of slot discharge (millivolts)	160	165
Max. PD Magnitude at Vph. pC	5000	3600
Visual inspection / Examination	Stator winding was moderately contaminated with carbon dust. No symptoms of deterioration due to time-temperature effects, corona / mechanical damage, wedges were found to be tight.	Slight carbon contamination of the stator winding. No symptoms of deterioration due to time-temperature effects, corona / mechanical damage, wedges were found to be tight.

Tan delta, ΔT, ΔC, IDE and Vi indicate low level of deterioration of the stator insulation. The overall structural integrity of the stator insulation is found to be healthy as no symptoms of deterioration due to thermal effects and mechanical damage were observed.

3.0 CONCLUSIONS

This paper shares the experience gained by the authors in dielectric diagnosis of several HV machines in service. Dielectric loss angle / capacitance and partial discharge are valuable condition assessment techniques and can detect the ageing mechanisms occurring in the stator insulation of rotating machines. Each has its own merits and merits and consequently each has a role in the overall assessment of the machine.

4.0 ACKNOWLEDGEMENT

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